

STRUCTURAL BEHAVIOUR OF PRECAST LIGHTWEIGHT FOAMED
CONCRETE SANDWICH PANEL (PLFP) WITH SHEAR TRUSS
CONNECTORS

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DEDICATION

For my beloved family, friends and supportive supervisors



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ABSTRACT

Precast system is playing a very important role in industrialize building system to construct more affordable and quality houses to meet the high demands. Many researches have been carried out to develop precast sandwich wall panel with more benefits such as lighter in weight, environmental friendly and easy to construct compared to normal reinforced concrete panel. Therefore, a study was carried out to develop Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) with shear truss connectors. The objectives of this study are to numerically investigate the PLFP panel with single and double shear truss connectors to determine its structural behaviour with validation from experimental work and to develop the empirical equation to predict its ultimate strength under axial load. PLFP panel is made of foamed concrete as the outer wythes which enclose a core layer of polystyrene. The wythes were reinforced with steel bars and tied to each other through the polystyrene layer by using steel shear connectors (bent at an angle of 45°). Experimental testing had been conducted to determine the material properties of foamed concrete and steel bar and used for PLFP model in finite element analysis. Eight half scaled PLFP panels were tested experimentally under axial load until it failed. Ultimate load carrying capacity, load lateral deflection profile, strain distributions and failure mode were recorded. Finite element analysis was carried out on PLFP panels which were validated with experimental results. Full scaled PLFP panels with single and double shear truss connectors had been studied numerically to investigate the effects of geometrical imperfection, slenderness ratio, thickness, and shear connectors toward its structural behaviour. From the results, it was found that when the rate of geometrical imperfection and slenderness ratio of PLFP panel increased, the ultimate load of PLFP panel decreased. The use of double shear truss connectors indicated improvement in the PFLP's strength and stability under axial load and longitudinal shear force compared to single shear truss connectors. An empirical equation which was modified from previous research is proposed to predict the ultimate load carrying capacity of PLFP under axial load.

ABSTRAK

Sistem pratuang memainkan peranan yang penting dalam sistem bangunan pra fabrikasi di kilang untuk membina lebih banyak rumah mampu milik dan berkualiti untuk memenuhi permintaan yang tinggi. Banyak kajian telah dijalankan untuk membangunkan panel pratuang *sandwich* dengan lebih banyak faedah seperti lebih ringan, mesra alam dan mudah untuk dibina berbanding panel konkrit bertetulang yang biasa. Oleh itu, satu kajian telah dijalankan untuk membangunkan Panel Pratuang *Sandwich* dari konkrit ringan berbusa (PLFP) dengan penyambung ricih kekuda. Objektif kajian ini adalah untuk menyiasat panel PLFP dengan penyambung ricih kekuda tunggal dan berganda bagi menentukan kelakuan struktur panel berdasarkan unsur terhingga dengan pengesahan dari eksperimen dan untuk menerbitkan persamaan empirikal bagi meramalkan kekuatan muktamad yang boleh ditanggung di bawah beban paksi. Panel PLFP diperbuat daripada konkrit berbusa sebagai lapisan dinding luar dan polisterin sebagai lapisan dalam. Lapisan dinding luar telah diperkukuhkan dengan bar keluli dan terikat kepada satu sama lain melalui lapisan polisterin dengan menggunakan penyambung ricih kekuda keluli (dibengkokkan pada sudut 45°). Eksperimen telah dijalankan untuk menentukan ciri-ciri bahan konkrit berbusa dan keluli bar bagi digunakan untuk memodelkan PLFP dalam analisis unsur terhingga. Lapan panel PLFP yang berskala separuh telah diuji dibawah beban paksi sehingga ia gagal. Panel PLFP telah dikaji dengan menggunakan analisis unsur terhingga untuk menyiasat kesan ketidaksempurnaan geometri, nisbah kelangsingan, ketebalan, dan penyambung ricih ke atas tingkah laku strukturnya. Daripada hasil kajian, apabila kadar ketidaksempurnaan geometri dan nisbah kelangsingan panel PLFP meningkat, beban muktamad panel PLFP menurun. Penggunaan penyambung ricih kekuda berganda menunjukkan peningkatan dalam kekuatan dan kestabilan panel PFLP di bawah beban paksi dan daya ricih membujur berbanding kekuda penyambung ricih tunggal. Persamaan empirikal yang telah diubahsuai daripada persamaan empirikal yang diterbitkan dalam kajian terdahulu telah dicadangkan untuk meramal beban muktamad PLFP bawah pengaruh beban paksi.

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LIST OF SYMBOLS AND ABBREVIATIONS

b	-	Overall width of the cross section
B	-	Length
c/c	-	centre to centre
C	-	Concrete cover
D	-	Damage parameter
e	-	Eccentricity
E	-	Young's Modulus
h	-	Overall depth of the cross section
H	-	Height of panel
$\frac{H}{B}$	-	Aspect ratio
$\frac{H}{L}$	-	Aspect Ratio
$\frac{H}{t}$	-	Slenderness ratio
k	-	0.8 for wall brace top and bottom against lateral translation and restrained against rotation at one or both ends.
K	-	The ratio of the second stress invariant on the tensile meridian
pcf	-	<i>per cubic foot</i>
t	-	Overall Thickness
Ψ	-	Dilatation angle
σ	-	Stress
$\frac{\sigma_{bo}}{\sigma_{co}}$	-	The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress
σ_{c0}	-	Initial yield
σ_{cu}	-	Ultimate stress
σ_{max}	-	Maximum principal effective stress
σ_{t0}	-	Uniaxial tensile stress at failure
ε	-	Strain
ε_t^{pl}	-	Tensile equivalent plastic strains

ϵ_c^{pl}	-	Compressive equivalent plastic strains
ϵ	-	Flow potential eccentricity
η	-	Effective length factor, 1.0 for compressive strength of concrete at 28 days $\leq 50\text{MPa}$
ρ	-	Density
ν	-	Poisson Ratio
μ	-	<i>Viscosity parameter</i>
θ	-	Temperature
Φ	-	Diameter of shear connector (mm)
Φ	-	The strength of reduction factor (0.7 for reinforced member)
\emptyset	-	Factor taking into account curvature, including second order effects
ASTM	-	American Standard Test Method
BCA	-	British Cement Association
BS	-	British Standard
CFRP	-	Carbon Reinforced Polymer
CIDB	-	Construction Industry Development Board of Malaysia
CREAM	-	Construction Research Institute of Malaysia
C3D8R	-	Continuum three dimensional 8 node linear brick element
EC2	-	Eurocode 2
EPS	-	Expanded Polystyrene foam
EXP	-	Experimental Result
FE	-	Finite element
FEA	-	Finite Element Analysis
HA	-	Half scale panel
IBS	-	Industrialized Building System
LVDT	-	Linear Voltage Displacement Transducers
PCI	-	Precast Concrete Institution
PLFP	-	Precast Lightweight Foamed Concrete Sandwich Panel
PRIMA	-	1 Malaysia People's Housing Programme
PSI	-	Pounds per square inch
PS	-	PLFP with single shear truss connectors
R&D	-	Research and Development
R3D4	-	Three dimensional 4 nodes rigid element

R3	-	3 mm mild steel
R6	-	6 mm mild steel
SG	-	Strain Gauges
T3D2	-	Three dimensional 2 nodes truss element
UTHM	-	Universiti Tun Hussein Onn Malaysia
XPS	-	Extruded Polystyrene foam
A_c	-	The gross area of section
A_{sc}	-	The total area of steel used
A_{st}	-	Total area of longitudinal reinforcement
d_c	-	uniaxial damage variable due to compression
d_t	-	uniaxial damage due to tension
E	-	Modulus Young
E_o	-	Initial (undamaged) elastic stiffness/ initial modulus of the material
e_a	-	An additional eccentricity due to deflections in the wall
e_i	-	Additional eccentricity covering the effects of geometrical imperfection
e_o	-	First order of eccentricity
e_{tot}	-	$e_o + e_i$
f_{bo}/f_{co}	-	The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress
f_{cu}	-	The compressive strength of concrete
f_i	-	field variable
f_y	-	The tensile strength of the steel
G	-	Flow potential
J	-	Energy
K_c	-	The ratio of the second stress invariant on the tensile meridian
l_o	-	Effective length of the wall
N_u	-	Design axial strength per unit length of wall (N/mm)
N_{Rd}	-	Axial resistance of wall
p	-	Hydrostatic pressure stress
P_u	-	The ultimate strength of panel
q	-	Mises equivalent effective stress
σ_y	-	Initial yield

REFERENCES

- Abaqus 6.9 Documentation (2009). Dassault Systemes, Abaqus, Inc., United States
- Abdullah, R., Vidal, P. Paton-Cole, Samuel Easterling, W. F. (2007).
Quasi-static Analysis of Composite Slab. *Malaysian Journal of Civil Engineering*. 19(2). pp. 94-102
- American Concrete Institute (1992). *Building Code Requirements for Reinforced Concrete (ACI 318-89) and Commentary*. Michigan: ACI 318-89. 1992
- Artizabal-ochoa, J. D. (2012). Stability and Second order non-linear analysis of 2D multi-column systems semi rigid connections: Effects of Initial Imperfections. *International Journal of Non-linear Mechanics*. 47(5). pp. 537-560
- ASTM International (2010). *Standard Test Methods for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. West Conshohocken, PA: ASTM Standard C469/C469M-10.
- ASTM International (2004). *Standard Test Methods for Tensile Testing of Metallic Materials*. West Conshohocken, PA: ASTM Standard E8M-04,
- ASTM International (2005). *Standard Test Methods for Conducting Strength Tests of Panels for Building Construction*. West Conshohocken, PA: ASTM Standard E 72-10.
- Benayoune, A (2003). *Precast Concrete Sandwich Panel As A Building System*. Ph.D. Thesis. Universiti Putra Malaysia.
- Benayoune, A., Samad, A. A. A., Abang Ali, A. A. and Trikha, D. N. (2007). Response of pre-cast reinforced composite sandwich panels to axial loading. *Construction and Building Materials* 21. pp. 677-685
- British Cement Association (1994). *Foamed Concrete Composition and Properties*. 165-168. British Cement Association.
- British Standard Institution (1997). *Structural Use of Concrete BS8110*. London: BS 8110

- British Standard Institution (1994). *Eurocode 4: Design of composite steel concrete structures: Part 1.1. General Rules and Rules for Buildings*, DD ENV 1994-1-1, BSI London
- British Standard Institution (2004). *Eurocode 2: Design of Concrete Structures- Part 1-1 General Rules and rules for buildings*. London: BS EN 1992-1-1
- Boissonnade, N. and Somja, H. (2012). Influence of Imperfections in FEM Modeling of Lateral Torsional Buckling. *Proceeding of the Annual Stability Conference Structural Stability Research Council*. Grapevine, Texas. pp. 1-15.
- Construction Industry Development Board (CIDB) (2007). *Construction Industry Master Plan Malaysia 2006-2015*. Malaysia Construction Industry Development Board
- Eric, Q. S. (2006). Shear locking and hourglassing in MSC Nastran, ABAQUS and ANSYS. *MSC Software Users Meeting*.
- Falade, F., Ikponmwosa, E. and Fapohunda, C. (2013). A Study on the Compressive and Tensile Strength of Foamed Concrete Containing Pulverized Bone as Partial Replacement of Cement, *Pak. J. Engg. and Appl. Sci. Vol.13*, pp. 82-93
- Frankl, B. A., Lucier, G.W., Hassan, T. K., and Rizkalla, S. H. (2011). Behaviour of Precast, Prestressed Concrete Sandwich Wall Panels Reinforced With CFRP Shear Grid, *PCI Journal*, Spring. pp. 42-54.
- Gran, J. K. and Senseny, P. E. (1996). Compression Bending of Scale Model Reinforced Concrete Walls. *J. Eng. Mech.* 122. pp. 660-668.
- Harris, H. G. and Sabnis, G. M. (1999). *Structural Modelling and Experimental techniques*, 2nd Ed., Boca Raton, FL. CRC Press.
- Hassan, T. and Rizkalla, S. (2010). Analysis and design guidelines of precast, prestressed concrete, sandwich wall panels reinforced with CFRP grid. *PCI Journal*, spring . pp. 147-162
- Hazid, H. (2013, September 30). Affordable housing an on-going issue. *The Edge*. Retrieved from <http://www.pr1ma.my>
- Jankowial, T., and Lodygowski (2005). T. Quasi static failure criteria for concrete. *Foundations of Civil and Environmental Engineering*, Vol. 6. pp. 53-69. ISSN 1642-9303

- Jason, L., Cabot, G. P., Huerta, and Ghavamian, S. (2004). Damage and Plasticity for concrete behavior. *European Congress on Computational Methods in Applied Sciences and Engineering*, German. ECCOMAS. pp.1-16.
- Jeung, H. D. (2002) *Experimental and Theoretical Studies of Normal and High Strength Concrete Wall Panels*. Ph.D Thesis. Griffith University.
- Johnson, S. (2006). *Comparison of Nonlinear Finite Element Modeling Tools for Structural Concrete*. University of Illinois At Urbana Champaign. Retrieved October 7th 2013 at <http://epfl.ch>
- Joshani, M., Koloor, S. S. R. and Abdullah, R. (2012). Damage Mechanic Model for Fracture Process of Steel Concrete Composite Slabs. *Applied Mechanics and Materials Vol. 165*, pp. 339-345
- Kamar, K. A. M., Hamid, Z. A., Ghani, M. K., Egbu, C., and Arif, M. (2011). Collaboration Initiative on Green Construction and Sustainability through Industrialized Building Systems (IBS) in the Malaysian Construction Industry. *International Journal of Sustainable Construction Engineering and Technology*. pp.119-127
- Knappett, J. A., Reid, C., Kinmond, S. and O'Reilly, K. (2011). Small-Scale Modelling of Reinforced Concrete Structural Elements for Use in a Geotechnical Centrifuge. *Journal of Structural Engineering*, 137. pp. 1263-1271
- Krispanarayan, K. M. (1977) Interesting aspect of the empirical wall design equation. *ACI J Proc* ;74(5). pp. 204-207
- Kuddus, M. A. (2010). *Numerical Simulation on Buckling Failure of the Masonry Load Bearing Walls*. Advanced Masters in Structural Analysis of Monuments and Historical Construction. Technical University of Catalonia, Spain.
- Kunhanandan Nambiar, E.K. and Ramamurthy, K. (2006). Influence of Filler type on The Properties of Foam Concrete. *Cement and Concrete Composites, Vols. 28*. pp. 475– 480
- Lee, J. and Fenves, G. (1998). Plastic-Damage Model for Cyclic Loading of Concrete Structures. *J. Eng. Mech.*, 124(8). pp. 892–900.
- Leabu, V. F. (1959). Problems and Performance of Precast Concrete Wall Panels. *ACI Structural Journal. Vols. 56*, pp. 287-298.

- Liew, H. K. (2010) *The Strain and Stress Distribution of Precast Lightweight Foamed Concrete Sandwich Panel under axial loading*. Bsc, Thesis. Universiti Tun Hussein Onn Malaysia.
- Macdonald, S. (2011). *Research Paper: Supply and Demand in the Penang Housing Market: Assessing Affordability*. Penang Institute
- Mahbuba, B., Robert, G. D. and Alaa, E. E. (2007). *Numerical Simulations of the Behaviour of Partially Encased Composite Columns*. Canada: University of Alberta.
- Malaysia Government (1996). *Seventh Malaysia Plan*, Percetakan Nasional Berhad, Kuala Lumpur.
- Mohamad, N., Omar, W. and Abdullah, R. (2011). Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) Tested Under Axial Load: Preliminary Results. *Advanced Materials Research*. Vols. 250-253, pp. 1153-1162.
- Mohamad, N. and Mahdi, M. H. (2011). Testing of Precast Lightweight Foamed Concrete Sandwich Panel With Single and Double Symmetrical Shear Truss Connectors Under Eccentric Loading. *Advanced Materials Research*. Vols. 335-336, pp. 1107-1116.
- Mohamad, N. (2010). *The Structural Behaviour of Precast Lightweight Foamed Concrete Sandwich Panels As Load Bearing Wall*. Ph.D Thesis. Universiti Teknologi Malaysia.
- Mokhatar, S. N. and Abdullah, R. (2012). Computational Analysis of Reinforced Concrete Slabs Subjected to Impact Loads. *Int J. Of Integrated Engineering*, Vol . 4 No. 2, pp. 70-76
- Newberry, C. M., Hoemann, J. M., Bewick, B. T. and Davidson, J. S. (2010). Simulation of Prestressed Concrete Sandwich Panels Subjected to Blast Loads. *Structures Congress*, Orlamdo, Florida.
- Novoselac. S. , Ergic. T and Balicevic. P (2012). Linear and Nonlinear Buckling and Post Buckling Analysis of a Bar with The Influence of Imperfections. *Tehnicki vjesnik* 19 (3), pp. 695-701
- Oberlender G. D. and Everard N. J. (1977). Investigation of Reinforced Concrete Wall Panels. *ACI Journal Proceedings*. Vols. 74(6), pp. 256-263.
- PCI Committee. (1997). State-of- the-Art of Precast/Prestressed Sandwich Wall Panels. *PCI Journal*. vol. 42, no.2

- Pillai S. U., and Partharasathy C. V. (1977). Ultimate Strength and Design of Concrete Walls. *Journal of Building and Environment*. 12, pp. 25-29.
- Ramamurthy, K., Kunhanandan Nambiar, E. K. and Indu Siva Ranjani, G. A. (2009). Classification of Studies on Properties of Foamed Concrete .*Cement and Concrete Composites*, 3, pp. 388-396.
- Robinson, G., Palmeri, A. and Austin, S. (2011) Implications of EC2 on the Design of Simply Supported Precast RC Panels under Eccentric Axial Load. *Fib Symposium PRAGUE*, pp. 1-9. ISBN 978-80-87158-29-6
- Saheb, S.M. and Desayi, P. (1989). Ultimate Strength of RC Wall Panels in One Way In Plane Action. *Journal of Structural Engineering, ASCE, Vol. 115(10)*, pp. 2617-2630.
- Sabnis, G. M., Harris, H. G., White, R. N. and Mirza, M. S. (1983). *Structural Modeling and Experimental Techniques*. Englewood Cliffs: Prentice-Hall, INC.
- Scheirs, J. and Priddy, D. (2003). *Modern Styrenic Polymers: Polystyrenes and Styrenic copolymers*. Wiley Series in Polymer Science. The Atrium, Southern Gate, Chichester; John Wiley and Sons Ltd.
- Shuid, S. (2004). Low Medium Cost Housing in Malaysia: Issues and Challenges, *APNHR Conference*, The University of Hong Kong.
- Sultan Sidi, N. S. (2011). *Syarahan Perdana 2011: The Different Scenarios of Housing Problem in Malaysia*. Batu Pahat: Penerbit UTHM.
- Sumadi, S. R. and Ramli, M. (2008). *Development of Lightweight Ferrocement Sandwich Panels for Modular Housing and Industrialized Building System*. Universiti Teknologi Malaysia: Research Vote No: 73311.
- Texas Foam Inc (2011). Expanded Polystyrene (E.P.S) Handbook. Retrieved March 18, 2013 from p. 3 at <http://www.texasfoam.com/EPS-Book.pdf>
- Vaughan, D., Milner, D. and Gran, K. (2011). New methods for progressive collapse testing and simulation. *Structure Congress*, pp. 2358-2369
- Wahyu, K. (2005). *An Introduction to the Finite Element Method*. Singapore. McGraw-Hill Education (Asia).
- Wan Badaruzzaman, W. H., Shodiq, H. M. and Hamid, A. A. (2004). Performance of Infilled Profiled Steel Sheet Dry Board PSSDB Load Bearing Wall. *International Journal of Engineering, Transaction B: Applications*, 17(4).

Wright, H. (1998). The Axial Load Behaviour of Composite Walling. *J. Construct. Steel Res.* Vol.45, No. 3, pp. 353-375.

Xu. L and Wang. X. H. (2008). Storey Based Column Effective Length Factors with Accounting for Initial Geometric imperfections. *Engineering Structures* 30, pp. 3434-3444.

